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NANO-FUNGICIDES IN AGRICULTURE: RECENT ADVANCES, MECHANISMS, APPLICATIONS, CHALLENGES, AND FUTURE PERSPECTIVES

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ABSTRACT

Agriculture plays a crucial role in ensuring global food security and supporting economic development. However, crop production is continuously threatened by a wide range of fungal diseases that cause significant yield losses and deterioration of crop quality. Pathogenic fungi such as *Fusarium*, *Alternaria*, *Botrytis*, *Colletotrichum*, and *Magnaporthe* species are responsible for substantial economic losses in cereals, fruits, vegetables, and other agricultural commodities worldwide. Conventional fungicides have long been used as the primary strategy for disease management, but their extensive use has led to several challenges, including the development of fungicide resistance, environmental contamination, non-target toxicity, and reduced effectiveness due to rapid degradation and poor bioavailability. Recent advances in nanotechnology have introduced innovative approaches for improving crop protection through the development of nano-fungicides. These formulations utilize nanoparticles or nanocarriers to enhance the delivery, stability, and efficacy of fungicidal compounds. Nano-fungicides offer several advantages over conventional formulations, including controlled release, targeted delivery, improved solubility, enhanced adhesion to plant surfaces, and reduced application rates. Various nanomaterials, including metallic nanoparticles, metal oxide nanoparticles, polymeric nanoparticles, nanoemulsions, and bio-based nanocarriers, have demonstrated promising antifungal activity against a broad spectrum of plant pathogens. This review provides a comprehensive overview of the role of nanotechnology in agricultural disease management, focusing on the development, classification, mechanisms of action, and applications of nano-fungicides. The review also discusses environmental safety considerations, current challenges, and future opportunities associated with nano-enabled crop protection strategies. The integration of nanotechnology into plant disease management has the potential to improve agricultural productivity while reducing the environmental burden associated with conventional fungicide use. Continued research and responsible implementation of nano-fungicides may contribute significantly to sustainable agriculture and global food security in the coming decades.

INTRODUCTION

Agriculture is the foundation of human civilization and remains one of the most important sectors supporting global food security, economic development, and social stability. More than half of the world's population depends directly or indirectly on agriculture for food, employment, and income generation. In addition to providing food and raw materials, agriculture contributes significantly to national economies and plays a crucial role in sustaining rural livelihoods. With the global population projected to exceed 9 billion by 2050, agricultural production must increase substantially to meet the growing demand for food, feed, fiber, and bio-based products. However, achieving sustainable increases in crop productivity remains a major challenge due to various biotic and abiotic stresses affecting agricultural system [1].

Among the various factors limiting crop production, plant diseases represent one of the most serious threats to global agriculture. Plant pathogens, including fungi, bacteria, viruses, nematodes, and oomycetes, are responsible for substantial reductions in crop yield and quality each year. Among these, fungal pathogens are considered the most destructive because of their widespread distribution, rapid reproduction, and ability to infect crops at different stages of growth. Fungal diseases affect nearly all cultivated crops and can lead to severe economic losses if not effectively managed. It has been estimated that plant diseases account for approximately 20–40% of annual crop losses worldwide, resulting in billions of dollars in economic damage and posing significant challenges to global food security [2,3].

Fungal pathogens are particularly problematic because they can infect roots, stems, leaves, flowers, fruits, and seeds, thereby affecting both yield and product quality. Several fungal species have gained global importance due to their destructive nature and wide host range. For example, *Magnaporthe oryzae*, the causal agent of rice blast disease, is regarded as one of the most devastating plant pathogens and is capable of causing significant yield losses in rice-producing regions. Similarly, *Fusarium oxysporum* causes vascular wilt diseases in numerous economically important crops, while *Botrytis cinerea* is responsible for graymold disease affecting fruits, vegetables, and ornamental plants. Other important fungal pathogens include *Alternaria spp.*, *Colletotrichum spp.*, *Rhizoctonia solani*, and *Puccinia spp.*, all of which contribute significantly to agricultural losses worldwide [1,4].

The economic consequences of fungal diseases extend beyond yield reduction. Infected crops often exhibit poor quality, reduced market value, shortened shelf life, and increased post-harvest losses. Farmers are also forced to invest considerable resources in disease management practices, including fungicide applications, resistant varieties, and cultural control measures. These additional production costs can reduce profitability and place financial burdens on agricultural communities. Furthermore, fungal contamination of food products may result in the production of mycotoxins, which pose serious risks to human and animal health and can lead to trade restrictions and economic losses.To minimize the impact of fungal diseases, fungicides have become an essential component of modern crop protection programs. Chemical fungicides are widely used because they provide rapid and effective disease control and can be applied to a broad range of crops. Over the past several decades, numerous classes of fungicides, including triazoles, strobilurins, benzimidazoles, and dithiocarbamates, have been developed and successfully utilized in agricultural production systems. These compounds have contributed significantly to increased crop productivity and food availability by protecting crops from destructive fungal infections.

Despite their effectiveness, conventional fungicides are associated with several limitations that have raised concerns regarding their long-term sustainability. One of the most important challenges is the development of fungicide resistance. Continuous and repeated use of fungicides with similar modes of action has resulted in the emergence of resistant fungal populations, reducing the effectiveness of disease control programs. Resistant strains of pathogens such as *Botrytis cinerea*, *Fusarium spp.*, and *Alternaria spp.* have been reported in many agricultural regions, making disease management increasingly difficult.

Another major concern associated with conventional fungicides is their environmental impact. A substantial portion of applied fungicides fails to reach the intended target and is lost through runoff, leaching, volatilization, and degradation. These losses contribute to soil and water contamination and may adversely affect beneficial organisms, including pollinators, soil microorganisms, and aquatic species. In addition, excessive fungicide use can lead to the accumulation of chemical residues in agricultural products, raising concerns regarding food safety and human health.

The effectiveness of conventional fungicides is also limited by factors such as poor water solubility, low bioavailability, rapid degradation under environmental conditions, and insufficient penetration into plant tissues. As a result, repeated applications are often required to maintain effective disease control, increasing production costs and environmental exposure. These limitations have created a need for innovative and sustainable approaches capable of improving crop protection while minimizing ecological risks.

In recent years, nanotechnology has emerged as a promising scientific and technological approach with the potential to transform agricultural practices. Nanotechnology involves the manipulation of materials at the nanoscale, typically between 1 and 100 nanometers, where unique physical, chemical, and biological properties can be exploited for various applications. The remarkable characteristics of nanoparticles, including high surface area, enhanced reactivity, improved stability, and controlled-release capabilities, have attracted significant attention in the field of crop protection.

The application of nanotechnology in agriculture has led to the development of nano-enabled pesticides, fertilizers, sensors, and delivery systems designed to improve agricultural efficiency and sustainability. Among these innovations, nano-fungicides have emerged as one of the most promising tools for managing fungal diseases. Nano-fungicides are formulations that either contain nanoparticles with intrinsic antifungal properties or utilize nanocarriers to improve the delivery and performance of conventional fungicidal compounds. These advanced formulations offer several advantages, including enhanced antifungal efficacy, targeted delivery, controlled release, improved stability, and reduced chemical consumption.Various nanomaterials, including silver nanoparticles, copper nanoparticles, zinc oxide nanoparticles, chitosan nanoparticles, nanoemulsions, and polymeric nanocarriers, have demonstrated significant potential in suppressing plant pathogenic fungi. Their ability to interact directly with fungal cells, generate reactive oxygen species, disrupt cellular structures, and improve fungicide delivery has opened new possibilities for sustainable disease management. Moreover, nano-fungicides may help address some of the major limitations associated with conventional fungicides, including resistance development, environmental contamination, and inefficient utilization.

Given the growing importance of sustainable agriculture and the increasing need for innovative crop protection strategies, nano-fungicides have become an active area of research worldwide. Numerous studies have reported encouraging results regarding their effectiveness against a wide range of plant pathogens affecting cereals, fruits, vegetables, and ornamental crops. However, challenges related to biosafety, environmental impacts, large-scale production, and regulatory approval still require careful consideration before widespread commercialization can be achieved [2].

Therefore, this review aims to provide a comprehensive overview of nanotechnology-enabled fungicides in agriculture. The article discusses the impact of fungal diseases on crop production, the limitations of conventional fungicides, the development and classification of nano-fungicides, their mechanisms of action, major agricultural applications, environmental considerations, and future prospects. By summarizing recent advances and current challenges, this review highlights the potential role of nano-fungicides in promoting sustainable crop protection and improving global agricultural productivity.

IMPACT OF FUNGAL DISEASES ON AGRICULTURE AND LIMITATIONS OF CONVENTIONAL FUNGICIDES

ECONOMIC IMPORTANCE OF AGRICULTURE AND FOOD SECURITY

Agriculture is one of the most important sectors supporting human survival, economic development, and global food security. It provides food, feed, fiber, and raw materials for numerous industries while also serving as a major source of employment in many countries. According to the Food and Agriculture Organization (FAO), the global demand for food is expected to increase significantly by 2050 due to rapid population growth and changing dietary patterns. To meet this growing demand, agricultural productivity must be improved while ensuring environmental sustainability. However, crop production is continuously threatened by various biotic and abiotic stresses, among which plant diseases represent one of the most serious challenges. Plant diseases reduce crop yield, lower product quality, and negatively affect the profitability of farming systems. Consequently, effective disease management has become an essential component of modern agricultural production.

Agricultural losses caused by plant diseases have direct and indirect impacts on food availability and economic stability. Reduced crop productivity can lead to food shortages, increased market prices, and decreased income for farmers. In developing countries, where agriculture remains a major contributor to the economy, disease outbreaks can have severe social and economic consequences. Therefore, protecting crops from disease-causing pathogens is critical for maintaining sustainable food production systems and supporting global food security [2].

MAJOR FUNGAL DISEASES AFFECTING AGRICULTURAL CROPS

Among the various plant pathogens, fungi are considered the most destructive because of their ability to infect a wide range of crops and spread rapidly under favorable environmental conditions. Fungal pathogens attack different plant parts, including roots, stems, leaves, flowers, fruits, and seeds, leading to significant reductions in crop yield and quality. Several fungal diseases have become major concerns in global agriculture due to their widespread occurrence and economic impact.

Rice blast disease, caused by *Magnaporthe oryzae*, is one of the most devastating diseases affecting rice cultivation worldwide. The pathogen infects leaves, stems, and panicles, causing characteristic lesions that reduce photosynthetic activity and grain production. Similarly, wheat rust diseases caused by *Puccinia* species pose a significant threat to wheat production and have been responsible for major epidemics in several countries. Fusarium wilt, caused by *Fusarium oxysporum*, affects numerous economically important crops, including tomato, banana, cotton, and chickpea. The pathogen invades the vascular system of plants, disrupting water transport and ultimately causing wilting and plant death.

Other important fungal diseases include anthracnose caused by *Colletotrichum* species, graymold caused by *Botrytis cinerea*, and leaf spot diseases caused by *Alternaria* species. These pathogens affect fruits, vegetables, cereals, and ornamental crops, leading to substantial economic losses during both cultivation and post-harvest storage. The widespread occurrence of these diseases highlights the importance of developing effective disease management strategies capable of protecting agricultural productivity [2,3].

ECONOMIC LOSSES CAUSED BY FUNGAL PATHOGENS

The economic impact of fungal diseases extends far beyond simple yield reduction. Plant pathogenic fungi are responsible for significant losses in agricultural productivity worldwide, with estimates suggesting that plant diseases account for approximately 20–40% of annual crop losses. In severe outbreaks, entire fields may be destroyed, resulting in substantial financial losses for farmers and agricultural industries.

In addition to reducing yield, fungal infections negatively affect crop quality and marketability. Fruits and vegetables infected with fungal pathogens often develop visible lesions, discoloration, and tissue degradation, making them unsuitable for commercial sale. Post-harvest fungal diseases further contribute to losses during storage, transportation, and marketing. Moreover, several fungal species produce mycotoxins that contaminate food and feed products, creating serious concerns regarding food safety and international trade. As a result, fungal diseases impose a considerable economic burden on agricultural systems worldwide and continue to threaten global food security [2].

CONVENTIONAL FUNGICIDES AND THEIR ROLE IN DISEASE MANAGEMENT

The management of fungal diseases has been a major focus of agricultural research for many decades. Among the various disease control strategies available, chemical fungicides remain the most widely used and effective tools for protecting crops against fungal infections. The introduction of fungicides revolutionized modern agriculture by providing farmers with a reliable means of preventing disease outbreaks and minimizing crop losses. As agricultural intensification increased during the twentieth century, fungicides became an essential component of crop protection programs and contributed significantly to improvements in agricultural productivity and food production [4].

Fungicides are chemical compounds specifically designed to inhibit the growth, reproduction, or survival of fungal pathogens. Depending on their mode of action, fungicides may prevent spore germination, disrupt cell membrane synthesis, inhibit respiration, interfere with cell division, or affect other essential biological processes within fungal cells. Their ability to provide rapid disease control has made them indispensable in the cultivation of cereals, fruits, vegetables, ornamental plants, and plantation crops.

Over the years, several classes of fungicides have been developed to combat a broad range of plant diseases. Among the most important are triazole fungicides, which inhibit ergosterol biosynthesis, an essential component of fungal cell membranes. Triazoles are widely used because of their broad-spectrum activity and systemic properties, allowing them to move within plant tissues and provide prolonged protection. Another important group is the strobilurin fungicides, which interfere with mitochondrial respiration and effectively suppress many foliar diseases affecting cereals and horticultural crops.

Benzimidazole fungicides have also played a significant role in plant disease management by disrupting fungal cell division. Although highly effective against several pathogens, their extensive use has led to the development of resistant fungal populations in many regions. Dithiocarbamate fungicides, such as mancozeb, are commonly used as protectant fungicides and act through multiple biochemical pathways, reducing the likelihood of resistance development. These fungicides continue to be widely employed in integrated disease management programs due to their broad-spectrum activity and relatively low cost [5].

The widespread adoption of fungicides has provided substantial benefits to global agriculture. By reducing disease incidence and severity, fungicides help maintain crop productivity, improve product quality, and increase economic returns for farmers. In many cases, the successful cultivation of high-value crops would not be possible without effective fungicide-based disease management programs. For example, intensive production systems for fruits and vegetables often rely heavily on fungicide applications to maintain marketable quality standards and minimize post-harvest losses.

In addition to their direct role in disease control, fungicides contribute to food security by protecting crops from devastating epidemics that could otherwise lead to significant reductions in food availability. Their use has become particularly important in regions where environmental conditions favor rapid disease development and where alternative disease management options may be limited. Consequently, fungicides remain one of the most important tools available for safeguarding agricultural production and ensuring stable food supplies.

Despite their undeniable contributions to crop protection, the increasing dependence on conventional fungicides has raised concerns regarding their long-term sustainability. Continuous use over several decades has revealed important limitations related to resistance development, environmental contamination, and potential impacts on human and ecosystem health. These challenges have prompted researchers to explore innovative approaches capable of improving fungicide performance while reducing associated risks.

LIMITATIONS OF CONVENTIONAL FUNGICIDES

Although conventional fungicides have played a critical role in modern agriculture, their continued and intensive use has exposed several limitations that threaten the sustainability of current disease management practices. One of the most significant challenges is the development of fungicide resistance among plant pathogenic fungi. Resistance occurs when fungal populations are repeatedly exposed to fungicides with the same mode of action, allowing naturally resistant individuals to survive and reproduce. Over time, these resistant strains become dominant, reducing the effectiveness of fungicide treatments and making disease control increasingly difficult [5-8].

The emergence of fungicide resistance has been reported in numerous economically important pathogens worldwide. Pathogens such as *Botrytis cinerea*, *Alternaria spp.*, *Fusarium spp.*, and *Zymoseptoria* *tritici* have developed varying degrees of resistance to commonly used fungicide classes, including benzimidazoles, triazoles, and strobilurins. As resistance becomes more widespread, farmers are often forced to increase application frequency, use higher doses, or switch to alternative fungicides, all of which increase production costs and environmental exposure. The growing prevalence of resistant fungal populations has therefore become a major concern for agricultural scientists and policymakers.

Environmental contamination is another important issue associated with conventional fungicide use. Following application, only a portion of the fungicide reaches the target pathogen. The remaining fraction may be lost through spray drift, surface runoff, leaching into groundwater, volatilization, or degradation processes. These losses can lead to the accumulation of fungicide residues in soil, water bodies, and surrounding ecosystems. In agricultural regions where fungicides are applied repeatedly, environmental contamination has become an increasing concern due to its potential effects on biodiversity and ecosystem health [7].

Soil microorganisms are particularly vulnerable to fungicide exposure. Many beneficial microorganisms contribute to nutrient cycling, organic matter decomposition, nitrogen fixation, and plant growth promotion. Excessive fungicide residues may disrupt these microbial communities, affecting soil fertility and ecological balance. Similarly, fungicide contamination of aquatic environments can negatively impact fish, algae, amphibians, and aquatic invertebrates. Such ecological effects highlight the need for more environmentally friendly disease management strategies that minimize non-target exposure.

Human health concerns have also attracted considerable attention in recent years. Agricultural workers involved in fungicide manufacturing, handling, and application may experience direct exposure through inhalation, skin contact, or accidental ingestion. Although safety regulations and protective equipment help reduce these risks, occupational exposure remains a concern in many agricultural settings. Consumers may also be exposed to fungicide residues present on food products, although regulatory agencies establish maximum residue limits to ensure food safety. Nevertheless, increasing public awareness regarding pesticide residues has intensified the demand for safer and more sustainable crop protection technologies [8].

Another limitation of conventional fungicides is their relatively low utilization efficiency. Many active ingredients possess poor water solubility and limited stability under field conditions. Exposure to sunlight, temperature fluctuations, rainfall, and microbial activity can accelerate fungicide degradation, reducing their effectiveness shortly after application. As a result, repeated spraying is often required to maintain adequate disease protection throughout the growing season. Frequent applications increase labor requirements, production costs, and the overall environmental burden associated with crop protection programs.

The lack of targeted delivery further contributes to fungicide inefficiency. Conventional formulations are generally applied uniformly across agricultural fields regardless of disease distribution. Consequently, a substantial proportion of the active ingredient may never reach the intended infection site. This inefficient delivery system not only reduces fungicide effectiveness but also increases the amount of chemical input required for satisfactory disease control. Such practices are increasingly viewed as incompatible with the principles of sustainable agriculture.

Economic considerations also play an important role in evaluating the limitations of conventional fungicides. Rising costs associated with fungicide development, registration, and repeated field applications can place considerable financial pressure on farmers, particularly in developing countries. In addition, losses resulting from resistance development and reduced fungicide performance may further increase production expenses. These challenges emphasize the need for innovative technologies capable of improving disease control while reducing chemical inputs and operational costs [2-5].

The combined effects of fungicide resistance, environmental contamination, human health concerns, poor delivery efficiency, and increasing economic pressures have highlighted the limitations of conventional disease management approaches. Consequently, researchers have focused considerable attention on developing advanced crop protection technologies that can overcome these challenges. Among the emerging solutions, nanotechnology has attracted significant interest because of its ability to enhance fungicide performance through improved delivery, controlled release, increased stability, and reduced environmental impact. The integration of nanotechnology into plant disease management has therefore opened new opportunities for the development of next-generation fungicides capable of supporting sustainable agricultural production.

CONVENTIONAL FUNGICIDES TO NANO-FUNGICIDES: AN EMERGING APPROACH FOR CROP PROTECTION

FUNGICIDES IN MODERN AGRICULTURE

Fungal diseases remain one of the most significant challenges to agricultural productivity worldwide. The continuous threat posed by fungal pathogens has made disease management an essential component of modern farming systems. Among the various disease control strategies available, fungicides continue to serve as the primary line of defense against fungal infections in crops. Their ability to provide rapid and effective disease suppression has contributed significantly to global food production and agricultural sustainability [1].

The use of fungicides has become deeply integrated into agricultural practices because they offer reliable protection against a wide range of plant pathogens. In cereal crops such as rice, wheat, and maize, fungicides are routinely applied to prevent diseases that can severely reduce grain yield and quality5. Similarly, horticultural crops including fruits, vegetables, and ornamental plants depend heavily on fungicide applications to maintain marketable quality and minimize post-harvest losses. The economic importance of fungicides is reflected in their widespread use across agricultural systems worldwide.

Over the years, numerous fungicidal compounds have been developed to combat different groups of fungal pathogens. Triazole fungicides are among the most widely used because of their broad-spectrum activity and systemic properties. Strobilurin fungicides are valued for their ability to provide preventive disease control and protect plant foliage from infection. Benzimidazole fungicides have historically played an important role in fungal disease management, while copper-based fungicides continue to be widely utilized in many cropping systems. Multi-site fungicides such as mancozeb are also commonly employed because they affect multiple biological processes within fungal cells and reduce the likelihood of resistance development.

The success of fungicides in agriculture can be attributed to their ability to interrupt critical physiological functions required for fungal growth and reproduction. Understanding these mechanisms is essential for appreciating both the strengths and limitations of conventional disease management strategies1–5.

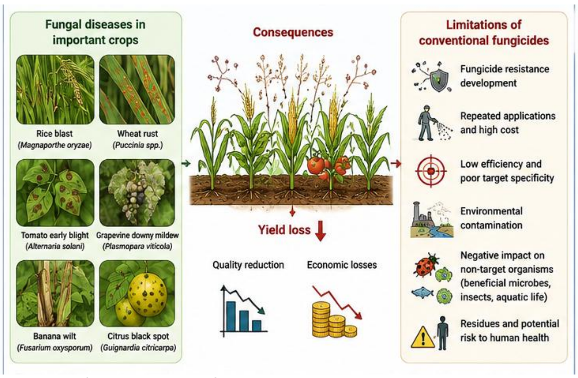


Figure 01 Impact of Fungal Diseases and Limitations of Conventional Fungicides

MECHANISMS OF ACTION OF CONVENTIONAL FUNGICIDES

Fungicides control plant diseases by targeting essential biochemical and physiological processes within fungal cells. Different classes of fungicides act through distinct mechanisms, but the ultimate objective is to inhibit fungal growth, prevent infection, or eliminate existing pathogen populations. The effectiveness of a fungicide depends largely on its ability to interfere with vital cellular functions required for survival and reproduction.

One of the most common mechanisms involves the inhibition of ergosterol biosynthesis. Ergosterol is a major component of fungal cell membranes and plays a role similar to that of cholesterol in animal cells. Triazole fungicides inhibit enzymes involved in ergosterol production, leading to defective cell membrane formation and impaired fungal growth. Without a functional membrane, fungal cells become unable to maintain normal physiological activities and eventually die.

Another important mechanism involves disruption of mitochondrial respiration. Strobilurin fungicides interfere with electron transport processes responsible for energy production within fungal cells. By blocking energy generation, these fungicides deprive pathogens of the resources necessary for growth and reproduction. As a result, fungal development is effectively suppressed [1].

Certain fungicides target fungal cell division. Benzimidazole fungicides interfere with microtubule formation during mitosis, preventing proper chromosome separation and cell replication. This disruption inhibits fungal proliferation and reduces disease development. In contrast, multi-site fungicides act on several biochemical pathways simultaneously, making it more difficult for pathogens to develop resistance.

Although these mechanisms have proven highly effective in controlling fungal diseases, the long-term dependence on conventional fungicides has revealed several important limitations. The emergence of resistant pathogen populations, environmental concerns, and inefficiencies in fungicide delivery have highlighted the need for improved disease management technologies [1–7,9].

CHALLENGES ASSOCIATED WITH CONVENTIONAL FUNGICIDE PERFORMANCE

Despite their widespread success, conventional fungicides are not without drawbacks. One of the most serious challenges is the increasing occurrence of fungicide resistance. Fungal pathogens possess remarkable genetic adaptability and can evolve resistance when repeatedly exposed to fungicides with the same mode of action. Over time, resistant individuals survive treatment and become dominant within pathogen populations, reducing the effectiveness of disease control programs.

The development of fungicide resistance has been documented in several economically important pathogens, including species of *Botrytis*, *Alternaria*, *Fusarium*, and *Puccinia*. Resistance not only compromises crop protection efforts but also forces farmers to increase application frequency or adopt alternative fungicides, often resulting in higher production costs. The growing prevalence of resistant strains represents a major threat to sustainable disease management [4,6].

Another limitation of conventional fungicides is their poor utilization efficiency. After application, a substantial portion of the active ingredient may be lost through environmental processes such as runoff, leaching, volatilization, and degradation. Consequently, only a fraction of the applied fungicide reaches the intended target pathogen. These losses reduce treatment effectiveness and contribute to environmental contamination.

Many fungicides also exhibit poor water solubility and limited stability under field conditions. Exposure to sunlight, temperature fluctuations, rainfall, and microbial activity can accelerate degradation and reduce biological activity. As a result, repeated applications are often necessary to maintain disease control throughout the growing season. Such practices increase labor requirements, production costs, and environmental burdens associated with crop protection.

Environmental concerns have become increasingly important in discussions regarding fungicide use. The accumulation of fungicide residues in soil and water may affect non-target organisms, including beneficial soil microorganisms, pollinators, aquatic species, and other components of agricultural ecosystems. In addition, public concern regarding pesticide residues in food products has stimulated interest in safer and more sustainable crop protection technologies8.

These challenges have encouraged researchers to investigate innovative approaches capable of improving fungicide performance while minimizing adverse environmental impacts. Among the emerging solutions, nanotechnology has shown exceptional potential for transforming agricultural disease management.

EMERGENCE OF NANO-FUNGICIDES

The growing limitations of conventional fungicides have created a strong demand for advanced crop protection technologies. Researchers have increasingly recognized that improving the delivery and utilization of fungicidal compounds may be just as important as developing new active ingredients. This realization has led to the exploration of nanotechnology as a promising tool for enhancing disease management in agriculture10.

Nanotechnology involves the manipulation of materials at extremely small dimensions, typically between 1 and 100 nanometers. At this scale, materials exhibit unique characteristics that differ from those observed in larger particles. Increased surface area, enhanced reactivity, improved stability, and controlled-release capabilities make nanoparticles particularly attractive for agricultural applications.

The application of nanotechnology to crop protection has resulted in the development of nano-fungicides, a new generation of fungicidal formulations designed to overcome many of the shortcomings associated with conventional products. Nano-fungicides are formulated either by incorporating fungicidal compounds into nanoscale carriers or by utilizing nanoparticles that possess inherent antifungal properties. These formulations are intended to improve delivery efficiency, enhance biological activity, and reduce environmental losses [10,11].

Unlike conventional formulations, nano-fungicides can provide controlled release of active ingredients over extended periods. This sustained release ensures that effective concentrations are maintained for longer durations, reducing the need for repeated applications. Furthermore, the small size of nanoparticles allows improved interaction with fungal cells and greater coverage of plant surfaces, enhancing disease suppression.

The emergence of nano-fungicides represents a significant advancement in agricultural science. By combining the disease-control capabilities of fungicides with the unique properties of nanomaterials, researchers have developed innovative formulations capable of improving efficacy while supporting sustainable agricultural practices [7,9–11].

CONCEPT AND CLASSIFICATION OF NANO-FUNGICIDES

Nano-fungicides can be broadly defined as fungicidal formulations that utilize nanotechnology to improve disease management performance. These systems may contain nanoparticles with direct antifungal activity or employ nanocarriers that deliver conventional fungicides in a more efficient and controlled manner. The primary objective of nano-fungicide development is to maximize disease control while minimizing chemical usage, environmental contamination, and non-target effects [9].

Based on their composition and functional characteristics, nano-fungicides can be classified into several categories. Metallic nanoparticle-based fungicides are among the most extensively studied systems. Silver nanoparticles, copper nanoparticles, and zinc nanoparticles have demonstrated strong antifungal activity against numerous plant pathogens. Their effectiveness is often attributed to their ability to disrupt fungal cell membranes, generate reactive oxygen species, and interfere with essential cellular processes [5].

Metal oxide nanoparticles represent another important group of nano-fungicides. Zinc oxide, copper oxide, titanium dioxide, and magnesium oxide nanoparticles have shown considerable potential in suppressing fungal growth. These materials are generally valued for their stability, ease of synthesis, and broad-spectrum antimicrobial properties.

Polymeric nano-fungicides utilize biodegradable materials such as chitosan, alginate, starch, and synthetic polymers as delivery vehicles for fungicidal compounds. These systems can encapsulate active ingredients and release them gradually over time, improving fungicide efficiency and reducing environmental exposure. Chitosan-based nanoparticles are particularly attractive because they possess both carrier functionality and intrinsic antifungal activity.

Nanoemulsions have also emerged as effective delivery systems for fungicidal compounds. These formulations consist of extremely small droplets that improve the dispersion and bioavailability of active ingredients. Their ability to enhance plant surface coverage and facilitate penetration into infection sites has generated significant interest in agricultural applications. The diversity of nano-fungicide formulations reflects the growing efforts to develop more effective and sustainable disease management technologies. Asresearch progresses, these systems are expected to play an increasingly important role in protecting crops against fungal pathogens while reducing the environmental impact of agricultural practices [5,7].

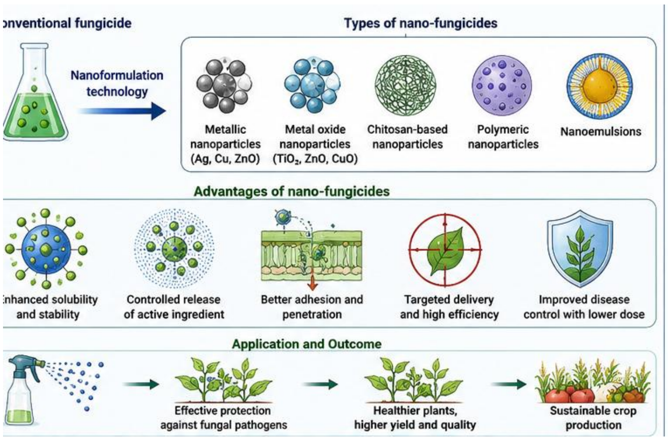


Figure 02: Development and Working Mechanism of Nano-Fungicides

Table 01: Classification of nano-fungicides, their representative nanomaterials, antifungal mechanisms, advantages, agricultural applications, and corresponding references.

Nano-fungicide Type	Representative Nanomaterials	Major Antifungal Mechanism	Advantages	Agricultural Applications	Reference
Metallic nanoparticles	Silver (AgNPs), Copper (CuNPs), Zinc (ZnNPs)	Disruption of fungal cell membrane, ROS generation, interference with proteins and nucleic acids	Broad-spectrum activity, multiple targets, reduced resistance development	Fusarium wilt, anthracnose, graymold, rice blast	5, 7, 13
Metal oxide nanoparticles	ZnO, CuO, TiO_2, MgO nanoparticles	ROS production, membrane damage, inhibition of nutrient transport	High stability, strong antimicrobial activity, easy synthesis	Cereals, fruits, vegetables, foliar diseases	8, 13
Chitosan-based nano-fungicides	Chitosan nanoparticles	Membrane disruption, leakage of intracellular components, induction of plant defense responses	Biodegradable, biocompatible, dual antifungal and elicitor activity	Post-harvest protection, Fusarium wilt, rice blast	11, 14
Polymeric nano-fungicides	Alginate, starch, cellulose derivatives, synthetic polymers	Controlled encapsulation and sustained release of fungicides	Improved stability, prolonged activity, reduced environmental losses	Targeted delivery of fungicides in crop protection	10, 13
Nanoemulsion-based fungicides	Nanoemulsions containing botanical fungicides and essential oils	Enhanced dispersion, improved penetration, increased bioavailability	Better plant surface coverage, reduced fungicide dose, eco-friendly formulation	Anthracnose, post-harvest diseases, powdery mildew	13, 15

TYPES OF NANO-FUNGICIDES AND THEIR ANTIFUNGAL MECHANISMS

The development of nano-fungicides has introduced new possibilities for managing plant diseases more effectively than conventional formulations. While traditional fungicides primarily depend on specific biochemical targets within fungal cells, nano-fungicides offer additional advantages through improved delivery, enhanced interaction with pathogens, and multiple modes of antifungal action. Depending on their composition and structure, nano-fungicides may act directly against fungal pathogens or function as carriers that improve the performance of existing fungicidal compounds. As research in agricultural nanotechnology continues to expand, several categories of nano-fungicides have emerged as promising tools for crop protection [9,12].

METALLIC NANOPARTICLE-BASED FUNGICIDES

Among the various nano-fungicide formulations, metallic nanoparticles have attracted considerable attention because of their strong antifungal properties. Their small particle size and large surface area enable close interaction with fungal cells, resulting in enhanced biological activity. Unlike many conventional fungicides that act through a single biochemical pathway, metallic nanoparticles often affect multiple cellular targets simultaneously, making it more difficult for pathogens to develop resistance [5,7].

Silver nanoparticles are among the most extensively studied nanomaterials for antifungal applications. Numerous studies have demonstrated their effectiveness against plant pathogens such as *Fusarium oxysporum*, *Alternaria alternata*, *Botrytis cinerea*, and *Colletotrichum* species. The antifungal activity of silver nanoparticles is primarily attributed to their ability to attach to fungal cell membranes, disrupt membrane integrity, and interfere with cellular metabolism. Once inside the cell, silver ions may interact with proteins, enzymes, and nucleic acids, ultimately leading to cell death. Because of their broad-spectrum activity, silver nanoparticles are considered one of the most promising candidates for next-generation disease management strategies [13].

Copper nanoparticles have also gained significant attention as potential alternatives to conventional copper-based fungicides. Copper compounds have long been used in agriculture for disease control, but nano-sized copper particles offer improved efficacy due to their increased surface area and enhanced reactivity. Studies have shown that copper nanoparticles can effectively suppress fungal growth by damaging cellular structures, generating oxidative stress, and disrupting essential metabolic processes. Their effectiveness against several economically important plant pathogens has encouraged continued research into their agricultural applications.

In addition to silver and copper nanoparticles, other metallic nanomaterials such as zinc nanoparticles have demonstrated promising antifungal activity. These nanoparticles can inhibit fungal growth through direct interactions with cellular components and by promoting the formation of reactive oxygen species. The ability of metallic nanoparticles to attack fungal pathogens through multiple mechanisms represents a significant advantage over many conventional fungicides [7].

Metal Oxide NANO-Fungicides

Metal oxide nanoparticles constitute another important category of nano-fungicides. These materials are valued for their chemical stability, ease of synthesis, and broad-spectrum antimicrobial properties. Among the various metal oxide nanomaterials investigated for agricultural applications, zinc oxide nanoparticles have received particular attention due to their strong antifungal activity and relatively low toxicity [8].

Zinc oxide nanoparticles have been reported to inhibit numerous fungal pathogens affecting cereals, fruits, and vegetables. Their antifungal effects are largely associated with the generation of reactive oxygen species, which can damage cellular membranes, proteins, and genetic material. In addition, zinc oxide nanoparticles may alter membrane permeability and interfere with nutrient transport processes within fungal cells. These combined effects ultimately inhibit fungal growth and reproduction.

Copper oxide nanoparticles have also demonstrated considerable potential in plant disease management. Similar to copper nanoparticles, copper oxide nanomaterials exert antifungal effects by inducing oxidative stress and disrupting essential cellular functions. Their effectiveness against pathogens responsible for leaf spots, wilts, and fruit rots has made them an attractive area of research.

Titanium dioxide nanoparticles represent another promising group of metal oxide nano-fungicides. Under light exposure, these nanoparticles can generate highly reactive molecules capable of damaging fungal cells. This photocatalytic activity provides an additional mechanism for suppressing plant pathogens and has stimulated interest in their use as environmentally friendly crop protection agents.

The broad-spectrum activity and stability of metal oxide nanoparticles have contributed significantly to their popularity in agricultural nanotechnology research. Their ability to function through multiple antifungal mechanisms makes them valuable candidates for future disease management applications [13].

CHITOSAN-BASED NANO-FUNGICIDES

Among bio-based nanomaterials, chitosan nanoparticles have emerged as one of the most promising platforms for agricultural applications. Chitosan is a natural polysaccharide derived from chitin, which is commonly found in the exoskeletons of crustaceans and insects. Due to its biodegradability, biocompatibility, and low toxicity, chitosan has attracted significant attention as a sustainable material for crop protection [11].

One of the unique characteristics of chitosan nanoparticles is their dual functionality. In addition to serving as carriers for fungicidal compounds, chitosan nanoparticles possess intrinsic antifungal properties. They can interact with fungal cell walls and membranes, increasing membrane permeability and causing leakage of intracellular contents. This disruption impairs normal cellular functions and inhibits fungal growth.

Chitosan nanoparticles have also been reported to stimulate plant defense responses. When applied to crops, they may activate defense-related enzymes and signaling pathways, enhancing the plant's natural resistance against pathogen attack. This ability to combine direct antifungal activity with host defense stimulation makes chitosan-based nano-fungicides particularly attractive for sustainable disease management [14].

Furthermore, chitosan nanoparticles can encapsulate conventional fungicides and release them gradually over time. Controlled release improves the persistence of active ingredients while reducing environmental losses and application frequency. These advantages have contributed to the increasing popularity of chitosan-based nano-formulations in agricultural research [11,14].

POLYMERIC NANO-FUNGICIDES

Polymeric nanoparticles are widely used as delivery systems for fungicidal compounds. Unlike metallic nanoparticles that primarily act through direct antimicrobial activity, polymeric nanomaterials focus on improving the transport, stability, and release of fungicides. These systems are commonly produced using biodegradable materials such as alginate, starch, cellulose derivatives, and synthetic polymers10.

The primary advantage of polymeric nano-fungicides lies in their ability to protect active ingredients from environmental degradation. Encapsulation within polymeric matrices shields fungicides from sunlight, temperature fluctuations, and microbial breakdown. As a result, the active compounds remain effective for longer periods following application.

Controlled release is another important feature of polymeric nano-fungicides. Instead of releasing the entire fungicide dose immediately, polymeric carriers gradually deliver active ingredients over an extended period. This sustained release maintains effective concentrations around the target pathogen while reducing the need for repeated spraying. Such improvements can enhance disease control efficiency while minimizing environmental contamination13.

Polymeric nanoparticles also improve fungicide solubility and facilitate better distribution on plant surfaces. By increasing the availability of active ingredients at infection sites, these systems contribute to more effective disease suppression. Consequently, polymeric nano-fungicides have become an important component of modern nanotechnology-based crop protection strategies [10,13].

NANOEMULSION-BASED FUNGICIDES

Nanoemulsions are another innovative class of nano-fungicide formulations. These systems consist of extremely small droplets, typically in the nanometer range, dispersed within a continuous liquid phase. Their small droplet size provides enhanced stability, improved dispersion, and greater contact with plant surfaces compared with conventional emulsions13.

Nanoemulsions are particularly useful for delivering hydrophobic fungicidal compounds that exhibit poor water solubility. By improving dispersion and bioavailability, nanoemulsion formulations can increase the effectiveness of active ingredients while reducing the quantity required for disease control. This characteristic is especially valuable for sustainable agricultural applications aimed at minimizing chemical inputs.

In recent years, researchers have increasingly explored the incorporation of botanical fungicides and essential oils into nanoemulsion systems. Many plant-derived compounds possess natural antifungal properties but suffer from poor stability and rapid degradation under field conditions. Nanoemulsion technology helps overcome these limitations by protecting bioactive compounds and enhancing their delivery to target pathogens [13].

The ability of nanoemulsions to improve surface coverage and facilitate penetration into infection sites further contributes to their effectiveness. As a result, these formulations are becoming increasingly important in the development of environmentally friendly crop protection products.

Antifungal Mechanisms of Nano-Fungicides

Although different nano-fungicides vary in composition and structure, many share common mechanisms of antifungal action. One of the most important mechanisms involves disruption of fungal cell membranes. Nanoparticles can attach to membrane surfaces, alter membrane structure, and increase permeability. This leads to leakage of cellular contents and loss of essential physiological functions.

Another major mechanism is the generation of reactive oxygen species (ROS). Many nanoparticles stimulate the production of highly reactive molecules that damage proteins, lipids, and nucleic acids within fungal cells. Excessive oxidative stress can overwhelm cellular defense systems and ultimately result in cell death9,12.

Nano-fungicides may also interfere with enzyme activity and metabolic pathways essential for fungal survival. By disrupting cellular metabolism, nanoparticles inhibit growth, reproduction, and pathogenicity. Certain nanoparticles can penetrate fungal cells and interact directly with DNA and RNA, affecting gene expression and cellular replication processes.

In addition to direct effects on pathogens, some nano-fungicides enhance plant defense mechanisms. Materials such as chitosan nanoparticles can activate defense-related signaling pathways, increasing the plant's ability to resist infection. This indirect mode of action provides an additional layer of protection against disease development.

The ability of nano-fungicides to operate through multiple mechanisms simultaneously distinguishes them from many conventional fungicides. This multifaceted activity not only improves disease control but may also reduce the likelihood of resistance development, making nano-fungicides an attractive option for future crop protection strategies [12].

APPLICATIONS OF NANO-FUNGICIDES IN CROP PROTECTION

The development of nano-fungicides has generated significant interest because of their potential to improve disease management across a wide range of agricultural crops. As discussed in the previous section, nano-fungicides possess several advantages over conventional formulations, including enhanced antifungal activity, controlled release, improved stability, and better interaction with fungal pathogens. These characteristics have encouraged researchers to evaluate their effectiveness against numerous economically important plant diseases. Results from laboratory, greenhouse, and field studies have demonstrated that nano-fungicides can successfully suppress various fungal pathogens affecting cereals, fruits, vegetables, and other agricultural commodities9.

The practical application of nano-fungicides extends beyond simple disease control. By improving the efficiency of fungicide delivery and reducing chemical losses, these formulations contribute to more sustainable crop protection practices. Their ability to maintain effective concentrations for extended periods may reduce application frequency and lower overall fungicide consumption. Consequently, nano-fungicides are increasingly viewed as a promising component of integrated disease management strategies aimed at enhancing agricultural productivity while minimizing environmental impacts [9,12].

Application Against Rice Blast Disease

Rice is one of the most important staple food crops in the world and serves as the primary source of nutrition for billions of people. However, rice production is continuously threatened by blast disease caused by *Magnaporthe oryzae*. This pathogen infects leaves, stems, nodes, and panicles, resulting in significant reductions in grain yield and quality. Under favorable environmental conditions, rice blast epidemics can cause severe economic losses and threaten food security in rice-producing regions9,12.

Conventional fungicides have traditionally been used to manage rice blast disease, but concerns regarding resistance development and environmental contamination have encouraged the search for alternative solutions. Nano-fungicides have emerged as promising candidates for improving disease management in rice cultivation. Studies have shown that silver nanoparticles, copper nanoparticles, and chitosan-based nano-formulations can effectively inhibit the growth and development of *M. oryzae*. These materials interfere with fungal cell integrity, suppress spore germination, and reduce pathogen colonization within plant tissues.

In addition to their direct antifungal activity, certain nano-formulations have been reported to stimulate plant defense mechanisms, enhancing the natural resistance of rice plants against infection. The combined effects of pathogen suppression and host defense activation contribute to improved disease control and increased crop productivity. As research continues, nano-fungicides may become valuable tools for sustainable rice disease management [12].

APPLICATION AGAINST FUSARIUM WILT

Fusarium wilt is one of the most destructive vascular diseases affecting agricultural crops worldwide. The disease is caused primarily by *Fusarium oxysporum*, a soil-borne pathogen capable of infecting numerous plant species, including tomato, banana, cotton, chickpea, and many vegetable crops. Once the pathogen enters the plant vascular system, it obstructs water transport, leading to wilting, yellowing, stunted growth, and eventual plant death.

The management of Fusarium wilt is particularly challenging because the pathogen can survive in soil for extended periods and often exhibits resistance to conventional control measures. Nano-fungicides have shown considerable promise in addressing these challenges. Silver nanoparticles, copper oxide nanoparticles, and chitosan nanoparticles have demonstrated strong inhibitory effects against *Fusarium* species in various experimental studies. These nanoparticles disrupt fungal cell membranes, induce oxidative stress, and interfere with cellular metabolism, ultimately suppressing pathogen growth.

The use of nano-fungicides against soil-borne pathogens offers several advantages. Controlled release systems can maintain effective concentrations in the rhizosphere for longer periods, improving disease suppression while reducing the need for repeated applications. Furthermore, biodegradable nano-carriers can facilitate targeted delivery of fungicidal compounds to infection sites, enhancing treatment efficiency and reducing environmental exposure. Such characteristics make nano-fungicides particularly attractive for managing persistent diseases such as Fusarium wilt [9].

APPLICATION AGAINST ANTHRACNOSE DISEASE

Anthracnose is a common fungal disease affecting numerous fruit, vegetable, and ornamental crops worldwide. The disease is primarily caused by species of *Colletotrichum* and is characterized by dark, sunken lesions on leaves, stems, flowers, and fruits. Anthracnose infections can significantly reduce crop yield, marketability, and post-harvest quality, resulting in substantial economic losses [11].

Conventional disease management often relies on repeated fungicide applications, which may contribute to resistance development and environmental concerns. Nano-fungicides have emerged as effective alternatives capable of providing enhanced disease control. Research has shown that metallic nanoparticles, particularly silver and copper nanoparticles, exhibit strong antifungal activity against *Colletotrichum* species. These nanoparticles inhibit spore germination, reduce mycelial growth, and impair pathogen development.

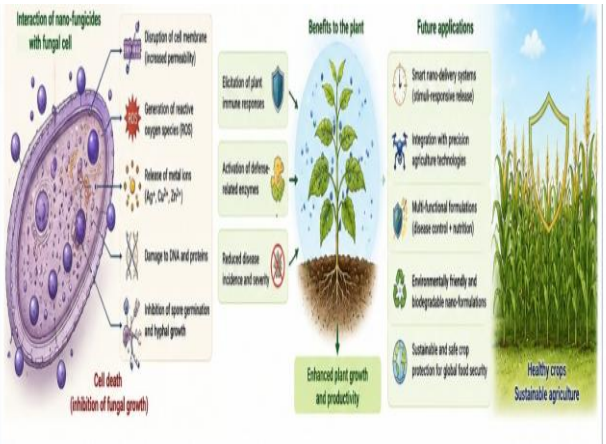
Nanoemulsion-based formulations containing natural antifungal compounds have also demonstrated promising results against anthracnose pathogens. By improving the stability and bioavailability of botanical fungicides, nanoemulsions can enhance disease suppression while reducing reliance on synthetic chemicals. Such approaches align with current efforts to develop environmentally friendly disease management strategies suitable for sustainable agriculture [12].

APPLICATION AGAINST GRAY MOLD DISEASE

Gray mold, caused by *Botrytis cinerea*, is among the most economically important fungal diseases affecting horticultural crops. The pathogen infects a wide range of fruits, vegetables, flowers, and ornamental plants, often causing severe losses during cultivation, storage, and transportation. Its ability to rapidly develop fungicide resistance has made disease management increasingly difficult in many production systems9.

Nano-fungicides have demonstrated considerable potential for controlling graymold disease. Studies involving silver nanoparticles, zinc oxide nanoparticles, and chitosan-based formulations have reported significant reductions in fungal growth and disease severity. These materials act through multiple mechanisms, including membrane disruption, oxidative stress induction, and interference with fungal metabolism.

Figure 02: Antifungal Mechanisms and Future Applications of Nano-Fungicides



An important advantage of nano-fungicides in graymold management is their ability to maintain prolonged antifungal activity through controlled release. This feature may reduce the frequency of fungicide applications and improve disease control under conditions favorable for pathogen development. Additionally, some nano-formulations have shown effectiveness in post-harvest disease management, helping extend the shelf life and quality of harvested produce [9,13].

APPLICATION AGAINST POWDERY MILDEW DISEASES

Powdery mildew diseases are caused by various fungal pathogens that produce characteristic white powder-like growth on plant surfaces. These diseases affect cereals, vegetables, fruits, ornamentals, and numerous other crops. Severe infections can reduce photosynthesis, impair plant growth, and decrease yield and quality.

The management of powdery mildew often requires multiple fungicide applications throughout the growing season. Nano-fungicides offer an attractive alternative because of their improved persistence and enhanced delivery efficiency. Research has shown that metal oxide nanoparticles and nanoencapsulated fungicides can effectively suppress powdery mildew pathogens by inhibiting spore germination and disrupting fungal development.

The small particle size of nano-formulations allows improved coverage of leaf surfaces, increasing contact between the fungicide and pathogen. This enhanced distribution contributes to more effective disease suppression and may reduce the amount of active ingredient required for treatment. Such benefits support the growing interest in nano-fungicides for managing foliar diseases in high-value crops [12].

APPLICATION IN POST-HARVEST DISEASE MANAGEMENT

Post-harvest fungal diseases represent a major source of agricultural losses worldwide. Fruits, vegetables, grains, and other commodities remain vulnerable to fungal infection during storage, transportation, and marketing. Pathogens such as *Penicillium*, *Aspergillus*, *Botrytis*, and *Colletotrichum* species are responsible for significant reductions in product quality and shelf life.

Traditional post-harvest disease management relies heavily on chemical fungicides, but increasing concerns regarding residue accumulation and consumer safety have encouraged the development of alternative approaches. Nano-fungicides have emerged as promising tools for post-harvest protection because of their ability to provide long-lasting antimicrobial activity and controlled release of active compounds [15].

Chitosan nanoparticles have been particularly successful in post-harvest applications due to their biodegradability, low toxicity, and natural antifungal properties. Coatings containing chitosan nanoparticles can create protective barriers on fruit surfaces while simultaneously suppressing pathogen growth. Similarly, nanoemulsions containing essential oils and plant-derived antifungal compounds have demonstrated effectiveness in reducing post-harvest infections and extending product shelf life.

The integration of nano-fungicides into post-harvest management strategies offers opportunities to reduce food losses, improve product quality, and decrease dependence on conventional chemical treatments. These benefits are especially important in developing countries, where post-harvest losses represent a significant challenge to food security [11,12,14,15].

CURRENT STATUS AND AGRICULTURAL POTENTIAL

The growing body of research on nano-fungicides highlights their potential to transform crop protection practices. Applications against diseases such as rice blast, Fusarium wilt, anthracnose, graymold, and powdery mildew have demonstrated encouraging results across diverse agricultural systems. In many cases, nano-fungicides provide disease control comparable to or better than conventional formulations while requiring lower application rates.

Furthermore, the versatility of nano-fungicides allows their incorporation into integrated disease management programs alongside biological control agents, resistant crop varieties, and cultural practices. Such integration may improve overall disease control efficiency while reducing environmental impacts associated with excessive chemical use.

Although large-scale commercial adoption is still developing, current research strongly suggests that nano-fungicides could become an important component of future agricultural systems. Continued advances in formulation technology, biosafety assessment, and regulatory approval processes are expected to further expand their role in sustainable crop protection.

CHALLENGES, ENVIRONMENTAL CONSIDERATIONS AND FUTURE PERSPECTIVES OF NANO-FUNGICIDES

The growing interest in nano-fungicides reflects the increasing need for innovative and sustainable approaches to plant disease management. As discussed in the previous sections, nano-fungicides offer several advantages over conventional formulations, including enhanced antifungal efficacy, improved stability, controlled release, and reduced chemical consumption. These characteristics have positioned nanotechnology as a promising tool for addressing many of the challenges associated with traditional fungicide-based crop protection. However, despite the encouraging results reported in laboratory and greenhouse studies, several scientific, environmental, economic, and regulatory challenges must be addressed before nano-fungicides can achieve widespread commercial adoption [8,13].

One of the primary concerns surrounding nano-fungicides is the limited understanding of their long-term environmental behavior. Unlike conventional fungicides, nanoparticles possess unique physicochemical properties that influence their movement, persistence, transformation, and interactions within agricultural ecosystems. After application, nanoparticles may enter soil, water, and plant systems, where they can undergo various physical and chemical changes. Factors such as particle size, surface charge, environmental conditions, and soil characteristics can influence their fate and biological activity. Although many studies have demonstrated the effectiveness of nano-fungicides against plant pathogens, comparatively less information is available regarding their long-term environmental impacts.

Soil represents one of the most important environmental compartments affected by agricultural nanomaterials. Since many nano-fungicides are applied directly to crops or soil, interactions with soil microorganisms are inevitable. Beneficial microorganisms play essential roles in nutrient cycling, organic matter decomposition, nitrogen fixation, and plant growth promotion. Therefore, understanding how nanoparticles influence microbial communities is crucial for evaluating the sustainability of nano-enabled crop protection technologies. While some studies have reported minimal adverse effects at recommended concentrations, others have suggested that excessive nanoparticle accumulation may alter microbial diversity and ecological balance. These findings highlight the need for comprehensive assessments under realistic agricultural conditions.

The potential impact of nano-fungicides on non-target organisms also remains an important area of investigation. Agricultural ecosystems support a diverse range of beneficial organisms, including pollinators, natural enemies of pests, earthworms, and aquatic species. Exposure to nanoparticles may occur through direct contact, contaminated water, or residue accumulation within the environment. Although nano-fungicides are generally expected to reduce overall chemical inputs compared with conventional formulations, their unique properties require careful evaluation to ensure that unintended ecological effects are minimized. Future research should focus on understanding nanoparticle interactions across different trophic levels and environmental conditions [8].

Human health considerations represent another critical aspect of nano-fungicide development. Agricultural workers may be exposed to nanoparticles during manufacturing, handling, transportation, and field application processes. Consumers may also encounter nanoparticle residues through food and water, although current evidence suggests that exposure levels are generally low when products are used appropriately. Nevertheless, the small size and high reactivity of nanoparticles raise questions regarding their potential biological interactions and long-term safety. Comprehensive toxicological studies are therefore necessary to establish safe exposure limits and support evidence-based regulatory decision-making.

In addition to environmental and safety concerns, economic factors may influence the adoption of nano-fungicides in agriculture. The synthesis and formulation of nanomaterials often require specialized equipment, advanced technologies, and rigorous quality control procedures. These requirements can increase production costs compared with some conventional fungicides. For widespread adoption, nano-fungicides must demonstrate not only superior performance but also economic feasibility for farmers. Advances in green synthesis methods, scalable manufacturing technologies, and cost-effective formulation strategies are expected to play important roles in improving commercial viability [6].

Regulatory challenges also represent a significant barrier to the commercialization of nano-fungicides. Existing pesticide regulations were primarily developed for conventional chemical formulations and may not adequately address the unique characteristics of nanomaterials. Regulatory agencies worldwide are actively working to develop guidelines for evaluating nano-enabled agricultural products, but harmonized standards are still evolving. Issues related to characterization, safety assessment, environmental monitoring, and labeling require careful consideration to ensure responsible development and public confidence in nanotechnology-based crop protection products.

Despite these challenges, the future prospects of nano-fungicides remain highly promising. Continued advances in nanotechnology are expected to drive the development of more efficient, environmentally friendly, and targeted disease management solutions. One important trend is the increasing emphasis on biodegradable and bio-based nanomaterials. Natural polymers such as chitosan, alginate, starch, and cellulose derivatives are attracting attention because of their biocompatibility, biodegradability, and low environmental impact. The use of such materials may help address concerns regarding nanoparticle persistence and ecological safety.

Another promising direction involves the integration of nano-fungicides with precision agriculture technologies. Modern agricultural systems increasingly utilize sensors, drones, artificial intelligence, and data-driven management approaches to optimize crop production. Nano-fungicides could be incorporated into these systems to enable more precise disease management based on real-time monitoring of crop health and pathogen activity. Such integration has the potential to improve treatment efficiency while reducing unnecessary chemical applications [7].

Researchers are also exploring multifunctional nano-formulations capable of performing several agricultural functions simultaneously. For example, future nano-fungicides may combine disease control, nutrient delivery, and plant growth promotion within a single formulation. Such multifunctionality could improve resource-use efficiency and contribute to more sustainable agricultural production systems. In addition, smart nano-delivery systems responsive to environmental stimuli such as pH, temperature, moisture, or pathogen presence are being investigated. These technologies may enable the controlled release of active ingredients only when and where they are needed, further improving efficiency and reducing environmental exposure [9].

The increasing global focus on sustainable agriculture and food security is likely to accelerate research and investment in nano-enabled crop protection technologies. As scientific understanding improves and regulatory frameworks become more established, nano-fungicides may gradually transition from experimental technologies to practical agricultural tools. Their ability to enhance disease control while reducing chemical inputs aligns closely with the goals of modern sustainable farming systems.

Overall, nano-fungicides represent a significant advancement in agricultural disease management. Although important challenges remain regarding environmental safety, regulatory approval, and commercial scalability, the potential benefits of these technologies are substantial. Continued interdisciplinary research involving plant pathology, nanotechnology, environmental science, toxicology, and agricultural engineering will be essential for realizing the full potential of nano-fungicides and ensuring their safe and effective use in future agricultural systems [13,15].

CONCLUSION

Fungal diseases continue to be one of the most significant constraints to agricultural productivity worldwide, causing substantial yield losses, economic damage, and threats to food security. Conventional fungicides have played a crucial role in protecting crops from fungal pathogens and supporting modern agricultural production. However, the increasing occurrence of fungicide resistance, environmental contamination, human health concerns, and poor utilization efficiency has highlighted the need for more sustainable disease management approaches.

Nanotechnology has emerged as a promising solution capable of overcoming many limitations associated with traditional fungicide formulations. The development of nano-fungicides has introduced innovative strategies for improving crop protection through enhanced antifungal activity, controlled release, improved stability, and targeted delivery of active ingredients. Various nano-fungicide systems, including metallic nanoparticles, metal oxide nanoparticles, polymeric nanoparticles, chitosan-based formulations, and nanoemulsions, have demonstrated significant effectiveness against a wide range of plant pathogenic fungi.

Research conducted over the past decade has shown that nano-fungicides can successfully suppress important diseases such as rice blast, Fusarium wilt, anthracnose, graymold, and powdery mildew. In addition to providing effective disease control, these technologies offer to reduce chemical inputs, minimize environmental contamination, and support sustainable agricultural practices. Their ability to improve fungicide utilization efficiency represents a major advantage in the context of growing concerns regarding environmental protection and resource conservation.

Despite these promising developments, several challenges remain before nano-fungicides can achieve widespread commercial implementation. Issues related to biosafety, environmental fate, large-scale production, cost-effectiveness, and regulatory approval require further investigation. Comprehensive risk assessments and long-term field studies will be essential to ensure the safe and responsible use of nano-enabled crop protection products.

In conclusion, nano-fungicides represent a new generation of agricultural disease management technologies with the potential to transform crop protection practices. Continued scientific advancements, combined with appropriate regulatory frameworks and sustainable development strategies, are expected to facilitate their integration into modern agriculture. As global demand for food continues to rise, nano-fungicides may play an increasingly important role in enhancing agricultural productivity, reducing crop losses, and supporting long-term food security while promoting environmentally responsible farming practices.

FUTURE PERSPECTIVES

The future of nano-fungicides lies in the development of safer, more efficient, and environmentally sustainable formulations capable of addressing the evolving challenges of agricultural disease management. Advances in nanomaterial design, green synthesis methods,and smart delivery systems are expected to improve the performance and safety profile of future nano-fungicide products.

Particular attention should be directed toward biodegradable nanocarriers, plant-based nanoparticle synthesis, and precision agriculture integration. The combination of nano-fungicides with emerging digital farming technologies may enable highly targeted disease management strategies that optimize crop protection while minimizing environmental impacts. Furthermore, the development of multifunctional nano-formulations capable of simultaneously enhancing plant growth, nutrient utilization, and disease resistance may contribute to more resilient agricultural systems.

Future research should also prioritize long-term environmental monitoring, toxicological assessments, and field-scale validation studies. Establishing internationally harmonized regulatory guidelines will be essential for facilitating commercialization and public acceptance of nano-enabled agricultural products. Collaboration among researchers, industry stakeholders, regulatory agencies, and farmers will play a crucial role in translating laboratory discoveries into practical agricultural solutions.

With continued innovation and responsible implementation, nano-fungicides have the potential to become a cornerstone of sustainable crop protection, supporting global food security and agricultural productivity in the decades ahead.

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AUTHOR CONTRIBUTION

All the authors contributed equally.

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